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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

# WARTIME REPORT

ORIGINALLY ISSUED
September 1942 as
Advance Restricted Report

## A STUDY OF THE EFFECT OF ADVERSE YAWING MOMENT ON LATERAL MANEUVERABILITY AT A HIGH LIFT COEFFICIENT

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NACA

WASHINGTON

L-465

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ADVANCE RESTRICTED REPORT

A STUDY OF THE EFFECT OF ADVERSE YAWING MOMENT ON LATERAL MANEUVERABILITY AT A HIGH LIFT COEFFICIENT

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SUMMARY

A theoretical study has been made of the effects of aileron adverse yawing moment on lateral maneuverability at a high lift coefficient. The lift coefficient is considered representative of those obtainable with full-span flaps. The study includes the effects of changes in effective dihedral angle, vertical-tail area, and tail length. The ranges of parameter variations slightly exceed those considered normal for modern airplanes.

It is shown that the effectiveness of lateral control is seriously reduced by adverse yawing moments of the order of one-half the rolling moment. Practical variations in effective dihedral and vertical-tail area do not satisfactorily compensate for such large adverse yawing moments. In order to alleviate the effects of adverse yawing moment, the moment must be either eliminated, as with spoiler devices, or counteracted, as with the rudder.

INTRODUCTION

In reference 1 an analytical investigation of the effect of the directional stability and the dihedral of an airplane on the aileron effectiveness was reported. From this work it was concluded that, for the conditions assumed, the directional stability had an important effect on the aileron effectiveness, that is, on the amount of control obtained with a given aileron for a given deflection and stick force. The effects of aileron adverse yaw could be compensated for by a slight increase in the directional stability.

The airplane conditions for this study, however, were representative of relatively high-speed flight with a plain

wing, a case in which the adverse yaw of the aileron is small. The question has since arisen as to the applicability of the conclusions to low-speed flight of an airplane equipped with a full-span high-lift flap for which the aileron adverse yaw may approach 50 percent of the aileron rolling moment. If the conclusions of reference 1 held, it might be possible to compensate for the effect of this yawing moment by an increase in fin area.

The study reported in the present paper follows the same lines as that of reference 1. Comparative computations were made for a hypothetical airplane at a lift coefficient of 2.8 for several values of adverse yaw, tail area, dihedral angle, and tail length. The range for each item covered slightly exceeded the range of present-day practice. The hypothetical airplane used for the investigation was made different from that of reference 1 by assuming a higher wing loading and different radii of gyration to make it more representative of the present-day high-speed pursuit airplanes.

## METHOD

The method used in determining the theoretical lateral motions at a high lift coefficient is the same as that used in reference 1. It was considered sufficient for the present investigation, however, to include only one change in dihedral angle because the trends of the effects of change are probably similar to the trends indicated in reference 1. Extrapolation of the present analysis may therefore be attempted.

## SYMBOLS

$K_X$ ratio of radius of gyration about the X axis to span

$K_Z$ ratio of radius of gyration about the Z axis to span

$\mu$ ratio of mass of airplane to mass of air defined as $\rho S_w b$

$\rho$ standard density of air

$S_w$ wing area

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| | |
|---|---|
| $b$ | span |
| $C_l$ | rolling-moment coefficient |
| $C_n$ | yawing-moment coefficient |
| $C_Y$ | side-force coefficient |
| $\Gamma$ | effective wing dihedral angle, degrees |
| $\beta$ | angle of sideslip, radians |
| $S_f$ | vertical-tail area |
| $l$ | effective tail length |
| $\phi$ | angle of bank, radians |
| $\psi$ | angle of yaw, radians |
| $\phi_1, \phi_2, \ldots$ | maneuvers consisting of attainment of angle of bank $\phi$ in 1 second, 2 seconds, . . . |
| $C_{l_p}$ | partial derivative of $C_l$ with respect to $pb/2V$ |
| $C_{l_r}$ | partial derivative of $C_l$ with respect to $rb/2V$ |
| $C_{n_p}$ | partial derivative of $C_n$ with respect to $pb/2V$ |
| $C_{l_\beta}$ | partial derivative of $C_l$ with respect to $\beta$ |
| $C_{n_\beta}$ | partial derivative of $C_n$ with respect to $\beta$ |
| $C_{Y_\beta}$ | partial derivative of $C_Y$ with respect to $\beta$ |
| $C_{n_r}$ | partial derivative of $C_n$ with respect to $rb/2V$ |
| $p$ | rolling velocity, radians per second |
| $r$ | yawing velocity, radians per second |
| $V$ | flight velocity |
| $s$ | distance traveled in span lengths |

## ASSUMED AIRPLANE CHARACTERISTICS

A hypothetical pursuit-type airplane having a relatively high wing loading, a high maximum lift coefficient, and average radii of gyration was assumed for the investigation. Aerodynamic details are considered chiefly characterized by the assumed set of stability derivatives.

The total weight of the airplane is assumed to be 6000 pounds; the wing loading, 30 pounds per square foot; the radius-of-gyration ratios, $K_X = 0.125$ and $K_Z = 0.175$; the aspect ratio, 8; the taper ratio, 2:1; and the sweep angle, 0°. The ratio $\mu$ is 9.8 and the lift coefficient is 2.8. References 2, 3, and 4 were used for determining representative values of the stability derivatives. Those derivatives, which are usually considered independent of changes in vertical-tail area, dihedral, and tail length, are as follows:

$$C_{l_p} = -0.5$$

$$C_{l_r} = 0.700$$

$$C_{n_p} = -0.182$$

The principal effect of varying dihedral is a change in the amount of rolling moment due to sideslip. Thus,

| $\Gamma$ (deg) | $C_{l_\beta}$ |
|---|---|
| 0 | 0 |
| 5 | -.07 |

where $\Gamma$ is the effective dihedral angle.

For this or the other parameters given in the following paragraphs, the derivatives $C_{l_\beta}$, $C_{n_\beta}$, $C_{Y_\beta}$, and so forth, are basic values. The effective dihedral, area ratios, and so forth, are used for convenience in representing simultaneous changes of a number of derivatives as

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is actually the case when the area ratios are changed. The values of these items as corresponding to the basic derivatives are considered representative of a midwing monoplane with power off but will vary with interference effects. For example, moving the wing from a high to a low position will change the effective dihedral angle 5°. Power effects may reduce the value of $C_{n_\beta}$ to zero.

Changes in vertical-tail area influence the values of yawing moment and side force due to sideslip and yawing moment due to yawing. All other effects are considered small. Thus,

| $S_f/S_w$ | $C_{n_\beta}$ | $C_{Y_\beta}$ | $C_{n_r}$ |
|---|---|---|---|
| 0.04 | 0.0275 | −0.299 | −0.274 |
| .07 | .080 | −.404 | −.328 |
| .12 | .167 | −.578 | −.414 |

It was assumed that a vertical-tail area of 4 percent of the wing area balanced the unstable yawing moment of the fuselage and gave zero $C_{n_\beta}$ with the flaps retracted.

Tail length was varied in such a way as to keep the tail volume $\frac{l}{b}\frac{S_f}{S_w}$ constant. It was assumed that such a variation changed only the values of yawing moment due to yawing and side force due to sideslip. Yawing moment due to sideslip was assumed constant at 0.0275 in order to discern the effect of changing tail length. The effect of changes of tail length on the derivatives was as follows:

| $l/b$ | $C_{Y_\beta}$ | $C_{n_r}$ |
|---|---|---|
| 0.4 | −0.334 | −0.260 |
| .5 | −.299 | −.274 |
| .6 | −.275 | −.288 |

Ten different combinations of the parameters $\Gamma$, $S_f/S_w$, and $l/b$ are thus available for analysis. These

combinations are identified as cases and are numbered as follows:

| $S_f/S_w$ \ $\Gamma$ (deg) | 0 | 5 |
|---|---|---|
| 0.04 | 1 | 4 |
| .07 | 2 | 5 |
| .12 | 3 | 6 |

The cases involving changes in $l/b$ are

| $l/b$ \ $\Gamma$ (deg) | 0 | 5 |
|---|---|---|
| 0.4 | 1(a) | 4(a) |
| .5 | 1 | 4 |
| .6 | 1(b) | 4(b) |

Most installations of lateral-control devices produce a relatively large negative (adverse) yawing moment in addition to a positive rolling moment. The ratio of this adverse yawing moment to the rolling moment varies with $C_L$ and with the control type, and experiments at high lift coefficients with flaps indicate that this ratio may vary from slightly positive with spoiler devices to approximately −0.5 with drooped ailerons. Values of $C_n/C_l$ of 0, −0.25, and −0.50 are considered to cover this range.

Because all the numerical factors involved are nondimensional, the results are directly applicable to all airplanes geometrically similar to the type characterized by the set of numerical factors herein assumed.

## RESULTS AND DISCUSSION

The results of the investigation are presented in figures 1 to 5. Figures 1 to 3 give the variations in angle of bank, azimuth, and sideslip with the distance

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traveled in span lengths for various values of the parameters. The variations of the derivatives of the motions of figures 1 and 2 are the variations in $pb/V$ and $rb/V$ with the distance traveled in span lengths because

$$\frac{d\phi}{ds} = \frac{pb}{V}$$

and

$$\frac{d\psi}{ds} = \frac{rb}{V} \quad \text{(See reference 1.)}$$

Figure 4 shows the relation of the angle of sideslip to the angle of bank following control application and includes the effect of changing vertical-tail area and effective dihedral.

Figure 5 gives the reciprocals of cross plots of figure 1 at the instances 1, 3, 4, and 10 seconds (where 2.37 span lengths traveled are equivalent to 1 second for the assumed airplane) and shows the variation in the amount of control necessary to obtain an angle of bank $\phi$ within the specified intervals.

The effect of changing tail length on the lateral motions was determined by varying the ratio of tail length to span from 0.4 to 0.6, a range usually considered normal for present-day airplanes. The changes were made with the directional stability constant and with two values of effective dihedral. It was shown that changes in tail length in the range considered have no appreciable effect on the lateral motions. The motions then for cases 1(a) and 1(b) may be considered identical with case 1 and similarly cases 4(a) and 4(b) with case 4. The effect of changes in tail length can be neglected only for problems in which the assumptions made herein are not violated. This result, however, may be invalidated by a consideration of interference effects and changes in fuselage moments with tail length.

In the analysis of the data of the figures, the same criterions are employed as in reference 1. For optimum aileron control, it is considered desirable to attain as large a positive angle of bank as is feasible with a given positive control moment, to have the banking motion as nearly linear with time as possible, to prevent any initial

adverse heading, to obtain a subsequent linear variation of heading after an interval of 1 or 2 seconds, and to keep the angle of sideslip at a minimum.

Figure 1 shows the general effect of changing the amount of yawing moment accompanying the aileron rolling moment on the banking motions with different effective dihedral angles and vertical-tail areas. The indications are much the same as in reference 1 as far as the effects of dihedral and fin area are concerned. A decrease in the magnitude of the aileron adverse yawing moment for all the cases considered improves the banking motions. This effect increases as the vertical-tail area becomes small and as the effective dihedral becomes large.

Figure 2 shows the effect of changing the aileron yawing moment on the azimuth motion with different effective dihedral angles and vertical-tail areas. The azimuth motions are also improved by decreasing the aileron adverse yawing moment. As with the banking motions, the effects are greatest when the tail area is small and the effective dihedral large.

Figure 3 shows the sideslipping motions due to a unit rolling control moment with different amounts of accompanying yawing moment, effective dihedral, and vertical-tail area. The sideslip as shown by figure 3 is not appreciably affected by the changes in aileron adverse yawing moment considered, but these curves are based on a unit applied rolling moment. The effect on sideslipping of changes in the parameters is shown in figure 4 in which the angle of bank is the basis for comparison. The sideslip accompanying the banking motions becomes much larger as the aileron adverse yawing moment is increased. For large values of adverse yawing moment and small vertical-tail areas, increasing dihedral greatly increases the sideslip with respect to the angle of bank. When the effect of dihedral is large, the large angles of sideslip are probably caused by the secondary yawing velocity. In figure 4(a), in which the effect of dihedral is small, the adverse moment assisting the adverse yawing velocity is absent. In figures 4(b) and 4(c), the effect of dihedral is small when the adverse yawing is appreciably counteracted by vertical-tail area.

Whereas figure 3, which is based on a unit control moment, shows that sideslipping is reduced by increases in

effective dihedral, figure 4 shows that this effect must be altered somewhat if banking motions comparable in magnitude are taken as the basis for determining the effects of changes of dihedral. Increasing effective dihedral decreases the magnitude of the banking motion due to a unit rolling moment. Increasing dihedral, therefore, is not so effective a means of decreasing sideslip as figure 3 indicates.

Although figure 3 shows that increasing vertical-tail area decreases the sideslipping motion at the start of the motion, the sideslipping motion is finally increased during maneuvers sufficiently long. This effect is probably due to the fact that the airplane approaches spiral instability or becomes more spirally unstable as the vertical-tail area increases.

It appears then that changing the airplane parameters does not necessarily eliminate objectionable magnitudes of sideslips. Proper application and coordination of all controls must be relied upon.

Figure 4 shows the effect of adverse yawing moment produced by aileron deflections. In each case, losses in control efficiency are realized when adverse yawing moment accompanies the application of rolling moment. The magnitude of this effect may be demonstrated by considering an example. For instance, consider an airplane with an $S_f/S_w$ of 0.8 and no effective dihedral (fig. 5(a)). In order to perform the maneuver $\phi_1$ (which consists of attaining an angle of bank $\phi$ in 1 second), it is necessary to apply a rolling-moment coefficient per radian angle of bank of 0.200 if the ailerons produce a pure rolling moment. If the ailerons produce an adverse yawing moment of one-half the rolling moment, it is necessary, for the performance of the same maneuver, to apply a rolling-moment coefficient per radian of 0.255, an increase of 27 percent for the same result. An increase of 27 percent in the stick forces is also indicated if the stick forces are proportional to the moments applied. Conversely, if the aileron adverse yawing moment is reduced from 50 percent of the rolling moment to zero or is counteracted as with the rudder, a decrease in required rolling moment of 22 percent is realized. With the mechanical advantage between the stick and the ailerons held constant, the 22-percent decrease in required rolling moment indicates a 22-percent decrease in maximum stick forces for this maneuver. In this case, however, the maximum available stick travel is

not utilized. If the mechanical advantage is changed so as to take full advantage of the available stick travel, the stick force may be lightened about 40 percent and maintain the same effectiveness.

If a slower banking maneuver $\phi_2$, for example, is taken for the criterion, an increase in moments and stick forces of 53 percent is necessary if aileron adverse yaw is allowed to produce its effect. When the adverse yawing moment is counteracted, a 34-percent decrease is accomplished for a given relation between the stick and aileron movement. The adverse yawing moment considered is again half the rolling moment. If a revised aileron linkage is resorted to, the decrease in stick force will be about 55 percent.

The foregoing example involves an airplane without effective dihedral. Consider the airplane with an effective dihedral angle of $5^\circ$ and an $S_f/S_w$ of 0.08 (fig. 4(b)). The 1-second banking-maneuver criterion shows an increase of 32 percent in applied control moments for the same effectiveness. As in reference 1, it is indicated that the effect of dihedral is negligible for such short maneuvers. For longer maneuvers, $\phi_2$ for instance, a 97-percent increase in control moments is necessary to maintain equal effectiveness and, conversely, a net decrease of 49 percent in rolling moment is required if the adverse aileron yawing moment is counteracted.

Reference 1 had shown that the effects of adverse aileron yawing moment occurring at the lift coefficient of 1 could be reduced appreciably for all but rapid maneuvers by relatively slight increases in fin area. The present investigation shows that, proportionally, the effects of adverse yawing moment are the same but, because of the greater aileron yawing moment at the higher lift coefficient, the stick forces are seriously increased and the amounts of vertical-tail area needed for compensation appear impracticable.

It may be concluded that, for conventional ailerons, deterioration of aileron control at high lift coefficients depends to an appreciable extent upon the increase with lift coefficient of the ratio of aileron adverse yawing moment to rolling moment. In general, it is indicated that, although appreciable changes in the lateral motions are

effected by changes in the vertical-tail area and effective dihedral, the effects of changes in these parameters in an attempt to alleviate the effects of large aileron adverse yawing moment are insufficient within the practical range of the parameters.

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## CONCLUSIONS

The foregoing theoretical investigation of controlled lateral motions leads to the following conclusions:

1. Adverse aileron yawing moments of the order of one-half the rolling moment seriously reduce the effectiveness of the lateral control.

2. The effects of large adverse aileron yawing moments cannot be satisfactorily reduced by practical variations in effective dihedral angle or vertical-tail area. These adverse effects, however, should be considered in the design of the vertical tail.

3. In order to alleviate the effects of adverse aileron yawing moment, the yawing moment must be eliminated or directly counteracted, as with the rudder.

4. The effect on the lateral motions of changing tail length, while keeping the directional stability constant, appears to be negligible in the normal range of tail lengths for present-day airplanes.

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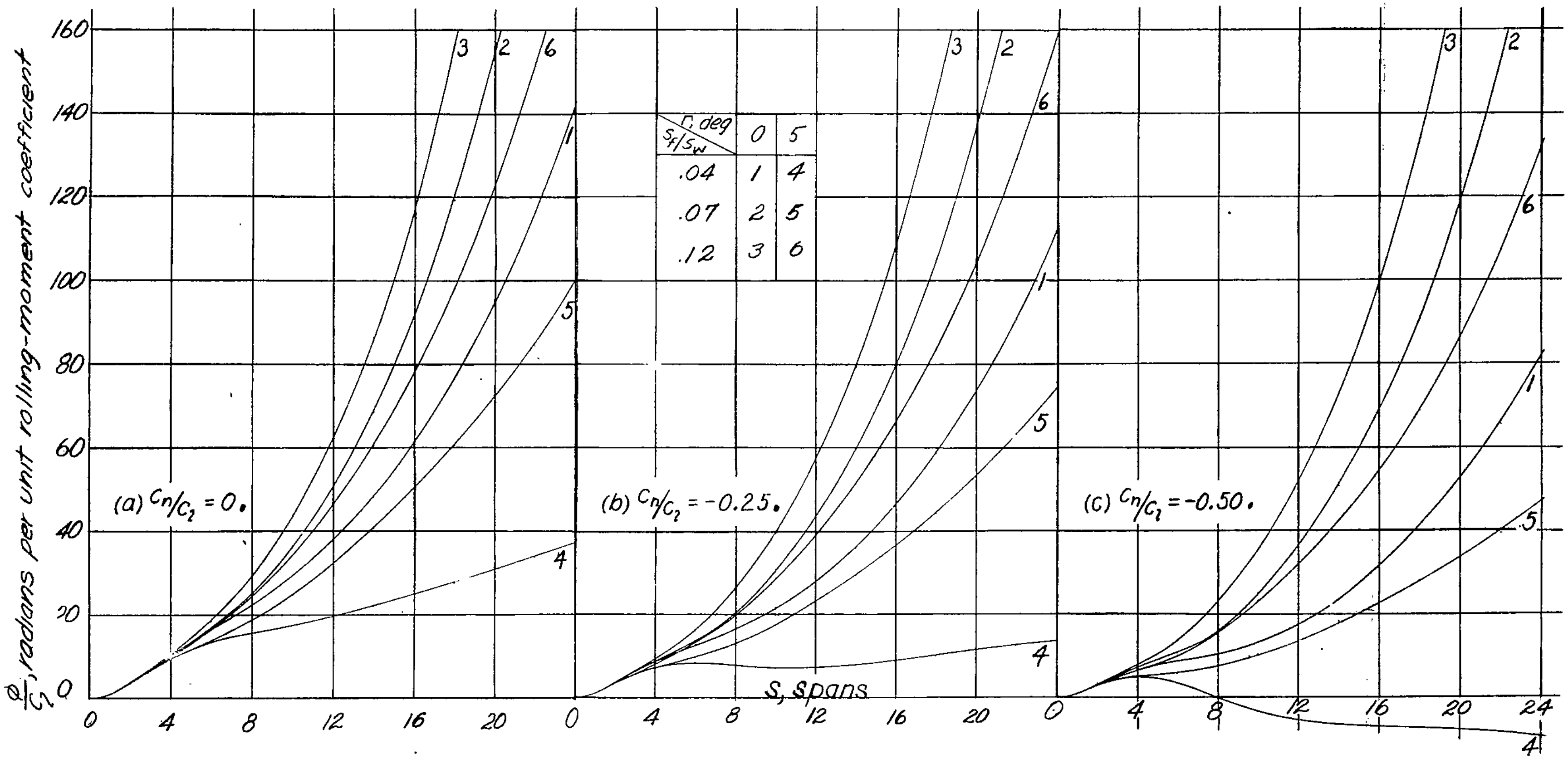


Figure 1.- The banking motion due to a unit rolling-moment coefficient as influenced by changes in vertical-tail area, dihedral, and control characteristics.

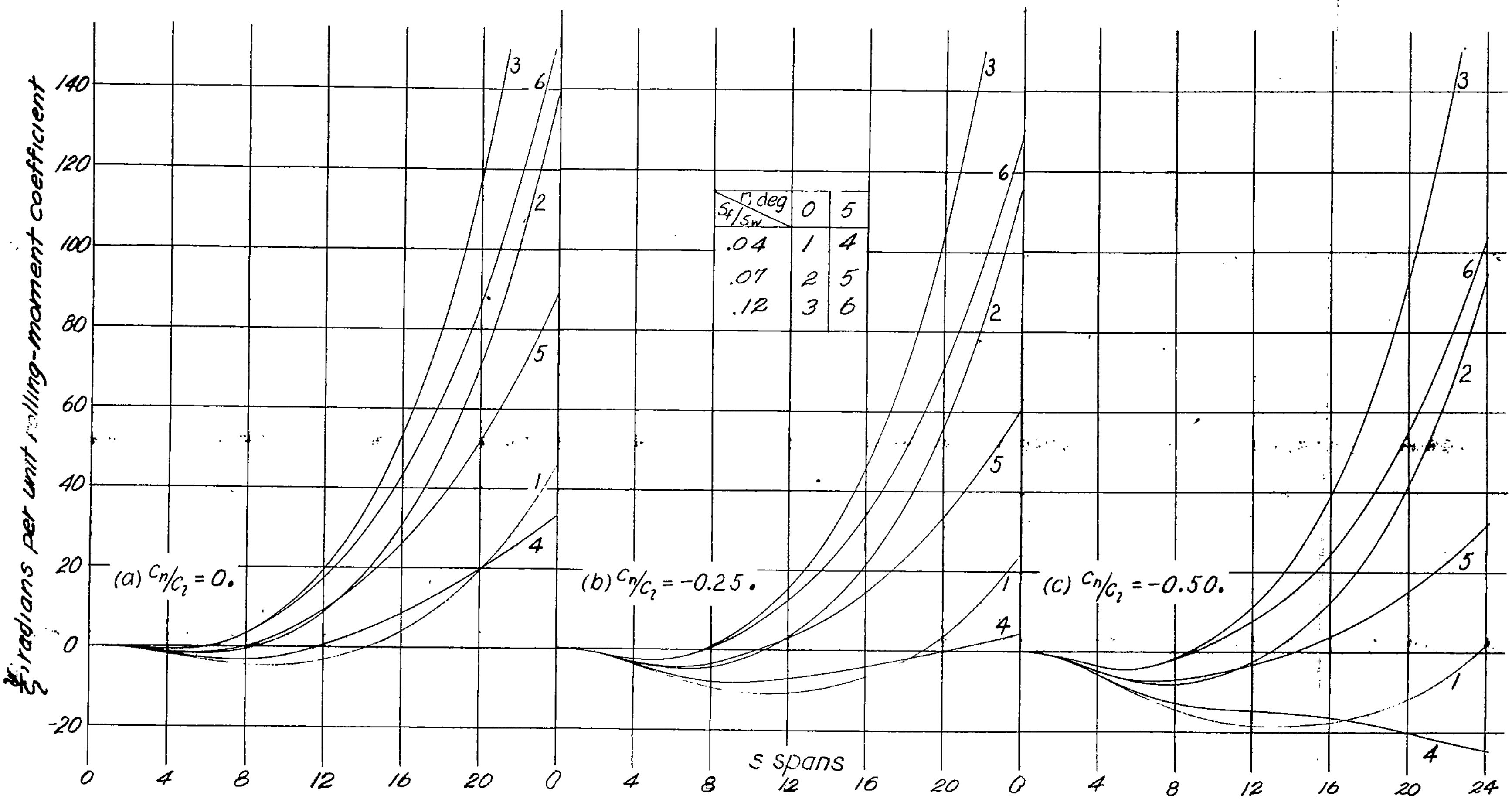


Figure 2.- The azimuth motion due to a unit rolling-moment coefficient as influenced by changes in vertical-tail area, dihedral, and control characteristics.

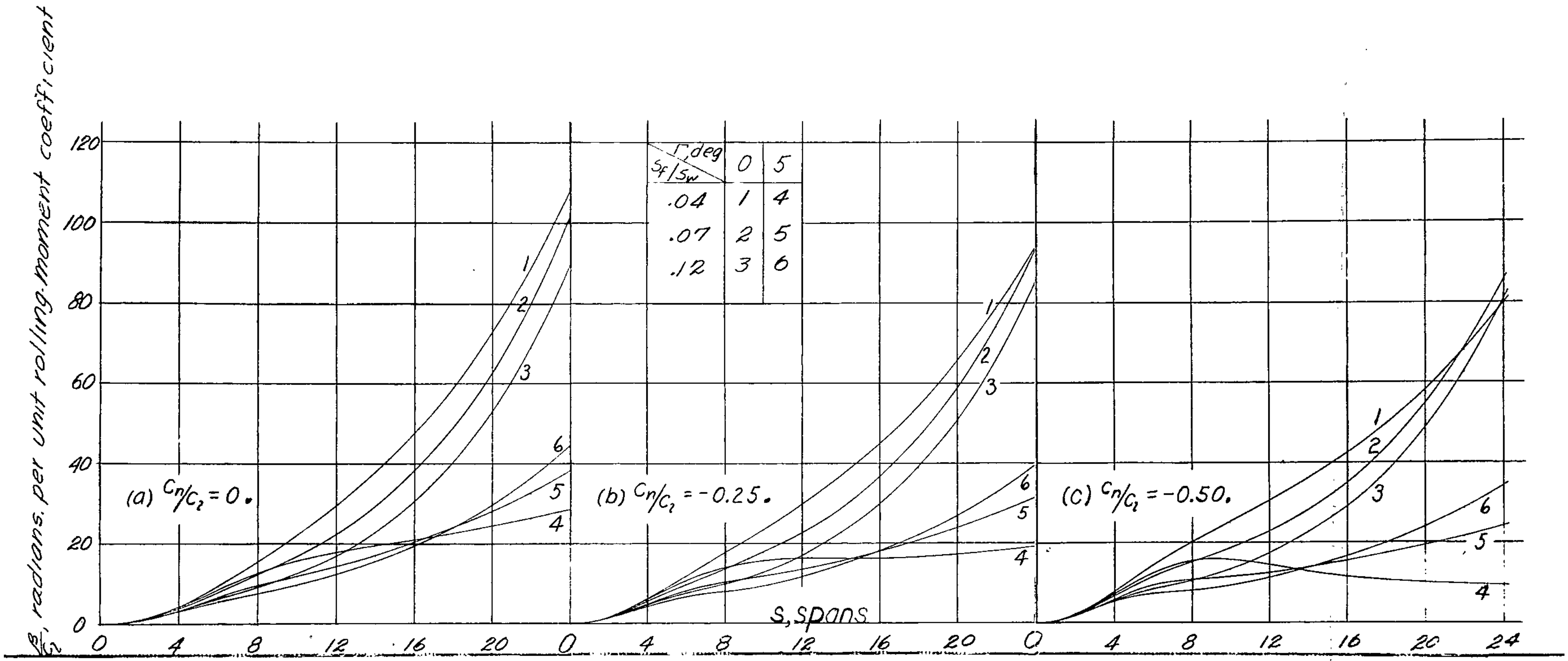


Figure 3.- The sideslipping motion due to a unit rolling-moment as influenced by changes in vertical-tail area, dihedral, and control characteristics.

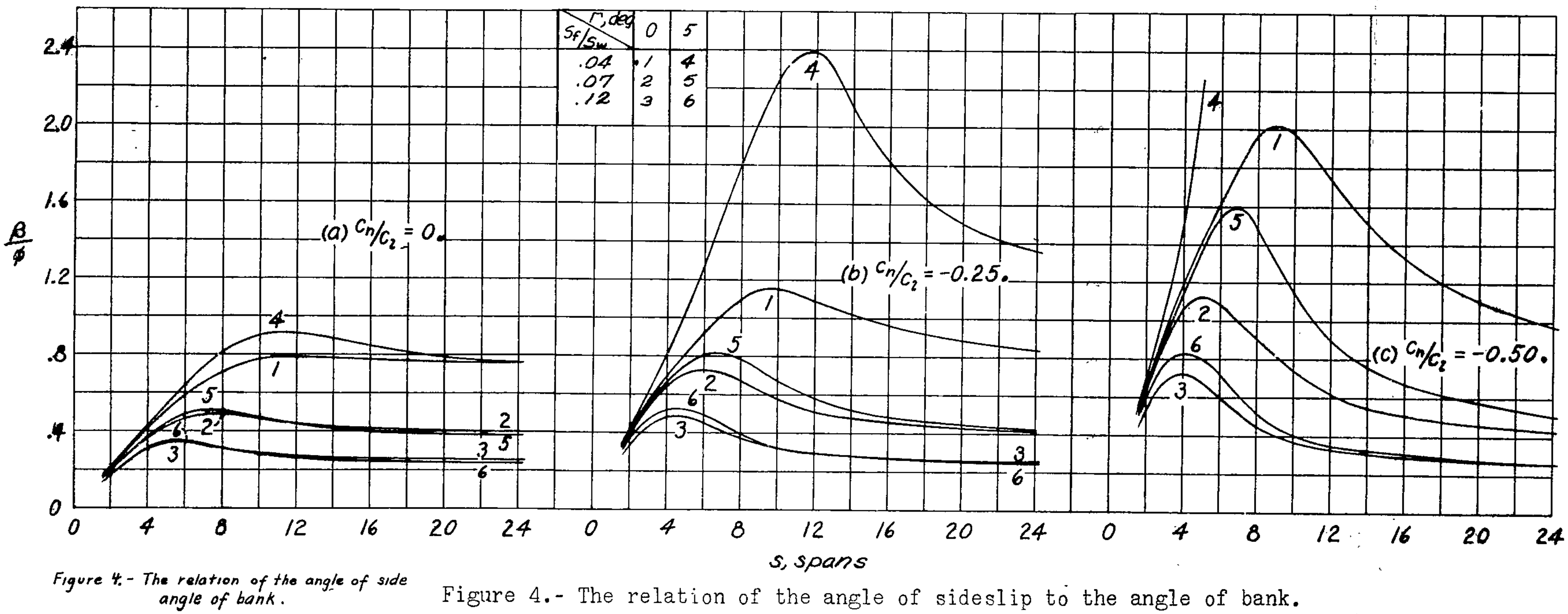


Figure 4.- The relation of the angle of sideslip to the angle of bank.

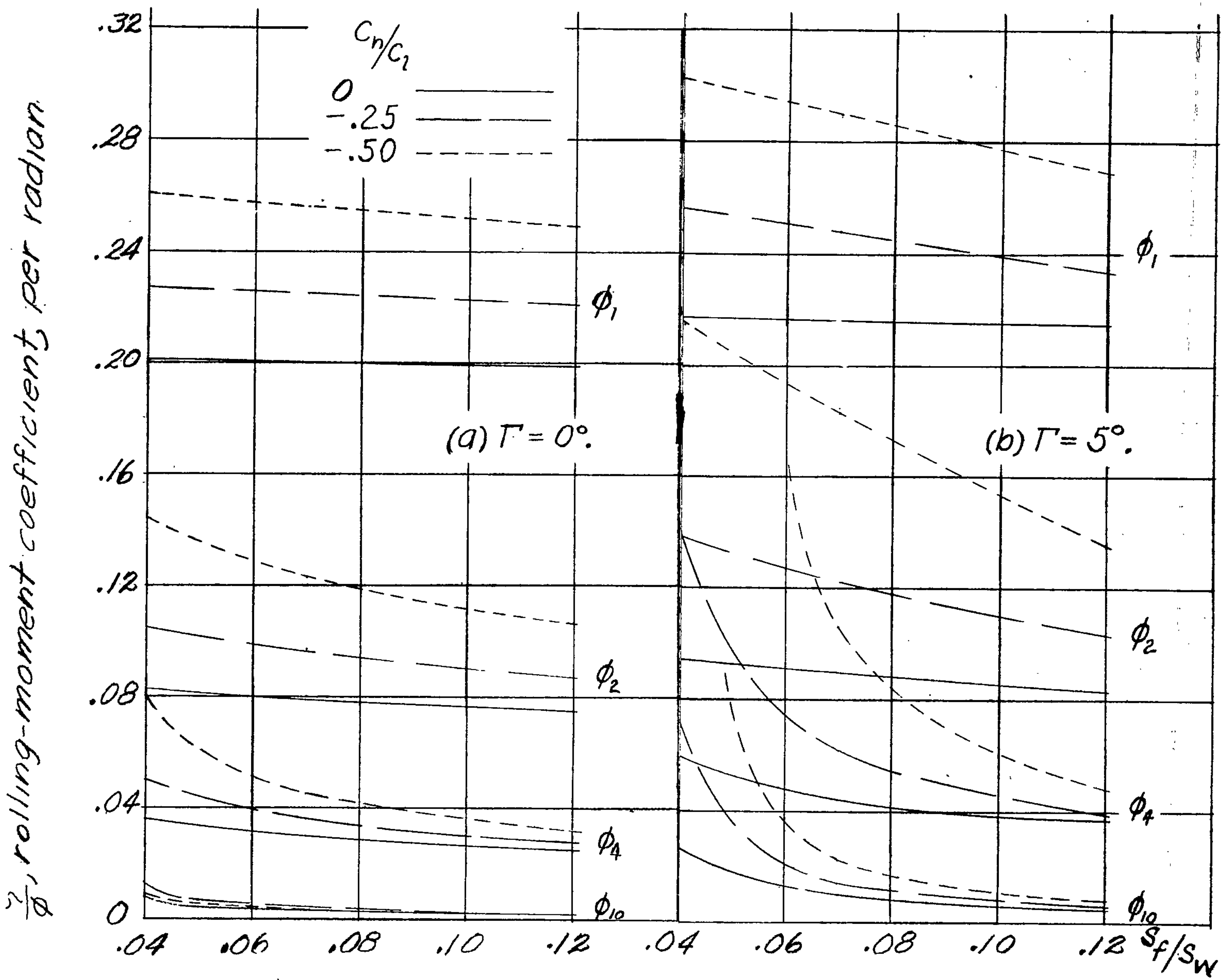


Figure 5.- The influence of changes in vertical-tail area, dihedral, and control characteristics on the magnitude of the control moment necessary to perform certain banking maneuvers.